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Fabric Filtration with Integral Particle Charging and Collection in a Combined Electric and Flow Field. Part 2 Development and Verification of the Mathematical Engineering Design Model

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16. ABSTRACT The paper discusses the development of a mathematical engineering design model to predict the nonuniform deposition of particulate matter and the relative pressure drop, compared to conventional filtration, of fabric filtration with integral particle charging and collection. For the model, the bag length is divided into a number of increments for each of which collections for the ESP and porous flow are computed separately. Turbulent flow within the bag requires the use of the Deutsch-Anderson relationship for the ESP collection. The relative pressure drop is calculated by first relating the computed areal density in each increment to the drag, which is resistance to flow. By use of the relationship for parallel resistance, the total drag is determined; the relative pressure drop is the ratio of the drag for the nonuniform flow to that for an equivalent quantity of particulate matter uniformly deposited by conventional filtration. The predictions for small test bags, whose operation was outside the range of assumptions used for model development, were qualitatively correct. For large fabric filtration bags of the size used in practical industrial applications, whose operation is within the range of assumptions, the model provides reasonably well-quantified predictions.

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FABRIC FILTRATION WITH INTEGRAL PARTICLE CHARGING AND COLLECTION IN A COMBINED ELECTRIC AND FLOW FIELD

PART II. DEVELOPMENT AND VERIFICATION OF THE MATHEMATICAL ENGINEERING DESIGN MODEL

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Summary

A mathematical engineering design model is developed to predict the nonuniform deposition of particulate matter and the relative pressure drop, compared to conventional filtration, of fabric filtration with integral particle charging and collection. For the model the bag length is divided into a number of increments for each of which collections for the ESP and porous flow are computed separately. Turbulent flow within the bag requires the use of the Deutsch-Anderson relationship for the ESP collection. The relative pressure drop is calculated by first relating the computed areal density in each increment to the drag, which is a resistance to flow. By use of the relationship for parallel resistance, the total drag is determined; the relative pressure drop is the ratio of the drag for the nonuniform flow to that for an equivalent quantity of particulate matter uniformly deposited by conventional filtration. The predictions for small test bags, whose operation was outside the range of assumptions used for the development of the model, were qualitatively correct. For large fabric filtration bags of the size used in practical industrial applications, whose operation is within the range of assumptions, the model provides reasonably well-quantified predictions.

1. Introduction

An experimental program had been undertaken to develop data on the nonuniform particle or dust layer deposition that results from fabric filtration with integral particle charging and collection in a combined electric and flow field [1,2]. On the basis of the results and data, a mathematical engineering design model will be developed and verified.

2. Approach to the development of the mathematical model

Prior to development of a mathematical engineering design model, it is necessary to determine the type of flow within the fabric filtration bag — laminar or turbulent.

It is claimed that in commercial electrostatic precipitators (ESPs) the flow is always turbulent with Reynolds numbers of 10,000 or more [3]. Inlet flow characteristics for a fabric filtration bag are similar to those of an ESP, and there usually is turbulence. However, the velocity decreases as the gas flows along the bag because of the flow through the porous walls, and it is possible for the turbulence to die out. It would be useful to determine the velocity characteristics in a fabric filtration bag containing integral particle charging and electric field. To accomplish this, it is necessary to determine the flow velocity through the porous walls as a function of position in the bag. In conventional fabric filtration with a uniform dust layer, the flow through the porous walls or face velocity, v_f, is a constant, which makes the velocity in the bag decrease linearly with position.

Whether or not a flow will be turbulent depends on whether the inertial or viscous forces in the flow dominate. The indication is given by the dimensionless Reynolds number:

$$Re = \frac{\rho}{\eta} vD \tag{1}$$

where ρ = gas density, η = viscosity, v = velocity, and D = characteristic diameter of the flow channel. If the Reynolds number is less than about 2100, the flow tends to be laminar because the viscous forces (indicated by the value of η) dominate. If the Reynolds number is greater than 2100, the flow tends to be turbulent because the inertial forces (indicated by the velocity) dominate [3].

For the electrified bags, flow data had been reported in terms of resistance to flow or drag, S, which had been defined as $\Delta P/v_f$. The reciprocal of S, which is $v_f/\Delta P$, is the face velocity for unit pressure [1]. At the time that the original data were taken, it appeared that, for a number of the cases, the value of $v_f/\Delta P$ changed linearly with the position in the bag. A typical example is shown in Fig. 1. It is believed that these areas of linearity occur in the portions of a bag in which there are good electrical conditions, which means uniform current distribution, corona, and no discontinuities.

There is support for the conclusion that the drag decreases and the face velocity increases with decreasing areal density. Based on reasonable assumptions, a mathematical discussion has suggested that a change in pressure drop would result from a nonuniform deposition of charged particles in a combined electric and flow field as compared to the pressure drop of a uniform deposition [4]. The argument was that the electrostatic, rather than the aerodynamic, forces will dominate in the location of the deposits and that it is possible to

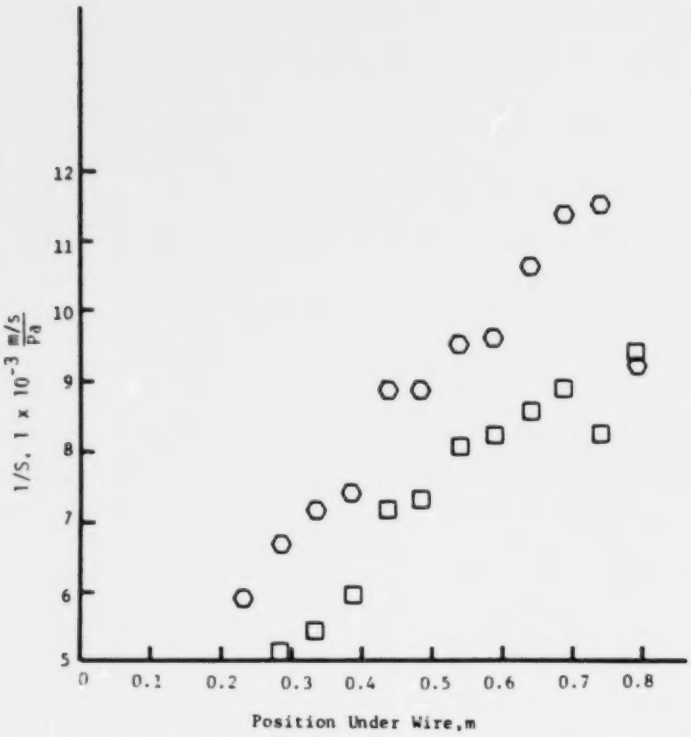

Fig. 1. Examples of linearity of face velocity at unit pressure vs. position under corona wire for two typical test runs.

continue to deposit dust electrostatically in regions of high areal density while the gas flows to the low areal density regions. It was further argued that the segregation of particles that result from the Coulombic collection will tend to maintain constant dust layer — k_2, specific dust cake resistance — properties. The ΔP was computed for both a step profile deposit and a bell-shaped continuous deposit as compared to uniform deposits of the same total mass of dust. The approach presented was in terms of differences in the deposition ratio between nonuniform and uniform deposits.

From the assumption of a constant k_2 factor for the nonuniform deposit, and using the relationship for drag, S, and areal density, W,

$$S = k_2 W \tag{2}$$

and the relationship for drag and face velocity, v_f, at constant pressure drop

$$S=\frac{\Delta P}{v_f}=k_2 W \tag{3}$$

Then it follows that the face velocity at constant pressure drop and k_2 is inversely proportional to the areal density [1,2].

The conclusion that the face velocity, at constant k_2, is inversely proportional to the areal density will be used to establish the flow field conditions in the mathematical model. Knowledge of the flow will be used shortly to determine whether laminar or turbulent flow conditions occur in the fabric filtration bag. Later, the relationship of eqn. (3), relating drag to areal density for a constant k_2, will be used to develop a relationship for computing the relative ΔP of a fabric filtration baghouse with integral particle charging and collection in a combined electric and flow field.

If it is assumed that v_f increases linearly with position, z, then

$$v_f=kz \tag{4}$$

For a differential element of length in the fabric filtration bag, the change in velocity is

$$\Delta v=-\frac{4k}{b}z\Delta z \tag{5}$$

in which z = position in the bag, Δz = length of the differential element, and b = diameter of the bag.

Taking eqn. (5) to the limit, and integrating with the conditions

$$v=v_0=\frac{4L\bar{v}_f}{b} \quad \text{for } z=0$$

$$v=0 \qquad \text{for } z=L$$

there results

$$v=\frac{4\bar{v}_f}{bL}(L^2-z^2) \tag{6}$$

in which b = bag diameter, L = length, v_0 = inlet velocity, and $\bar{v}_f$ = average face velocity.

The average face velocity (gas-to-cloth ratio) is established by the design of the baghouse. Substituting eqn. (6) into eqn. (1), noting that the characteristic diameter, D, is the diameter, b, of the bag, there results

$$Re=4\frac{\rho}{\eta}\bar{v}_f L\,(1-z^2/L^2) \tag{7}$$

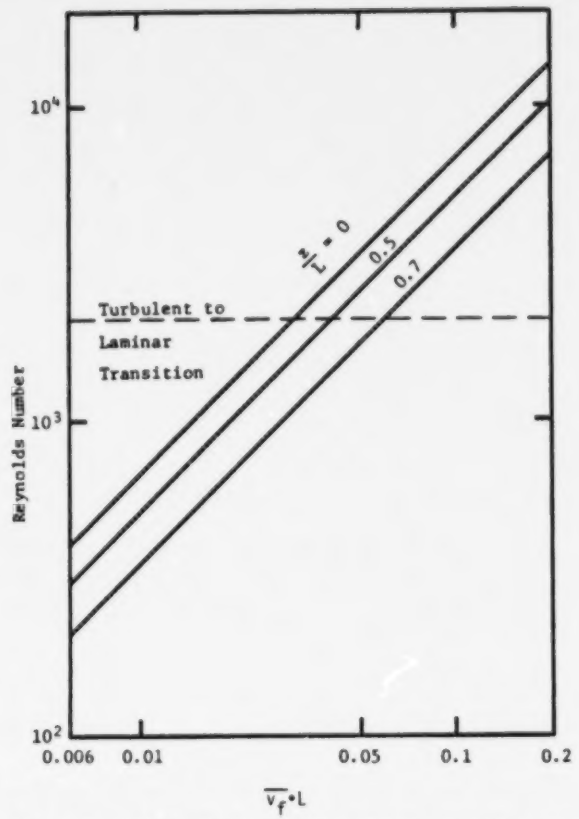

Fig. 2. Reynolds number as a function of the product of the gas-to-cloth ratio, $\bar{v}_f$, and bag length, L, for different positions in bag.

The Reynolds number is now known as a function of position, z, in the bag. Figure 2 is a plot of Re as a function of the product of $\bar{v}_f$ and L, for different values of z/L.

Short bags, especially with low gas-to-cloth ratios, will have relatively low Reynolds numbers that will tend to put them into the laminar flow regime. Longer bags, especially with high gas-to-cloth ratios, will have relatively high Reynolds numbers that would definitely be in the turbulent regime. Practical industrial application would use long bags that would have turbulent flow. Therefore, the flow will be assumed to be in the turbulent regime for the purpose of developing a mathematical model.

3. Development of the model

Over the past 15 years, Southern Research Institute has developed (for the Air and Energy Engineering Research Laboratory of the Environmental Protection Agency) a mathematical model for predicting the collection efficiency for an ESP. This ESP model development has been an evolutionary process [5–9]. The ESP model was initially developed with a number of simplifying assumptions (e.g., use of wire–pipe geometry for symmetry in the equations, and the neglect of re-entrainment in the collection zone). In subsequent revisions, the model has been improved in accuracy and usefulness [10].

The model divides the ESP into a number of increments of length in each of which the Deutsch–Anderson collection equation is applied. The Deutsch–Anderson collection equation is used because of the turbulent flow within the ESP [3]. The ESP is divided into increments to allow changing the electrical conditions from increment to increment.

For the ESP model, the Deutsch–Anderson collection equation

$$N = 1 - \exp\left(-\frac{A}{Q}w\right) \tag{8}$$

is evaluated for a narrow increment of particle size range. This results from a restriction for the Deutsch–Anderson expression that requires a uniform charge and migration velocity in the collecting zone. To obtain the penetration for the complete ESP, the penetration for each particle size increment is summed for all the length increments and finally summed again for all the size increments. This process is represented mathematically by

$$P_t = \sum_{i=1}^{m} \sum_{j=1}^{l} \exp\left(-\frac{A_j}{Q_j\, w_{ji}}\right) \tag{9}$$

In eqns. (8) and (9), A = collector area, Q = gas flow, and w = migration velocity; i = index for particle size, and j = index for incremental length . The term A/Q is often called the specific collector area (SCA). The amount collected $= 1 - P_t$.

The complete ESP model also has to take into account: (1) electrical condition determined by analytical, numerical, or empirical methods, (2) calculation of particle charging, and (3) calculation of migration velocities. In addition, corrections must be included for nonideal conditions including rapping re-entrainment, gas sneakage through nonelectrified regions, and nonuniform flow distribution. All of the above calculations plus a number of more subtle corrections are handled by fast, modern computing equipment.

In an ESP, the gas enters at the inlet and exits intact at the outlet. For fabric filtration, with integral particle charging and collection in a combined electric and flow field, the gas enters at the inlet but, unlike an ESP, only exits through

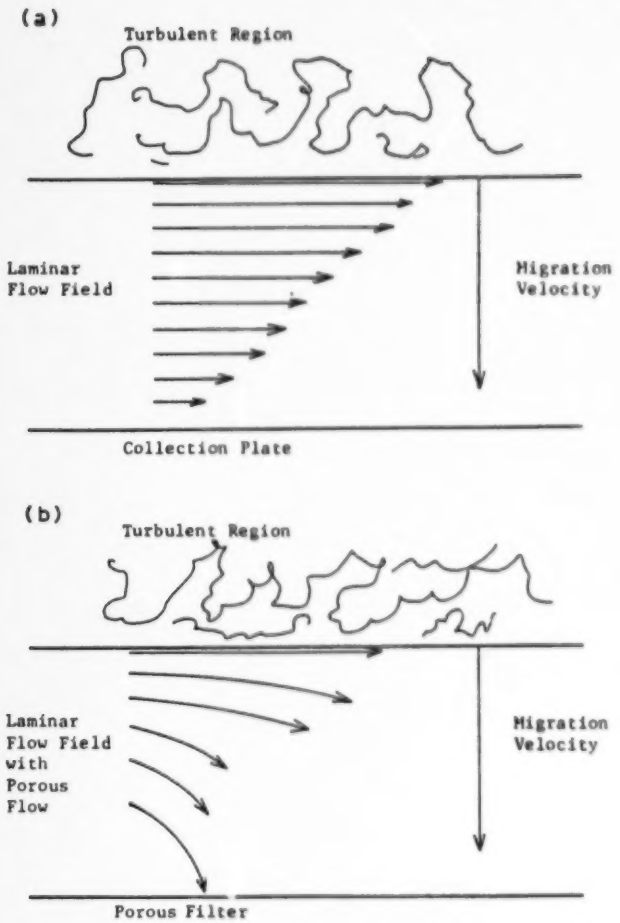

Fig. 3. Comparison of the laminar boundary layer for an ESP and for fabric filtration with integral particle charging and collection in a combined electric and flow field.

the porous fabric media. The porous flow causes the collection of some portions of the particulate matter. The remainder of the particulate matter is collected by the ESP effect. Thus, a mathematical model would require that both the ESP collection and porous flow collection be considered and included.

The assumption of turbulent flow in fabric filtration with integral particle charging and collection in a combined electric and flow field requires the use of the Deutsch–Anderson relationship. The porous flow will cause the gas flow quantity, Q, in eqn. (8) to decrease in going up the bag.

A consideration of the assumption of turbulent flow and the necessity to use

the Deutsch–Anderson equation are the flow differences in the boundary layer within a bag as compared to the boundary layer for an ESP. For the turbulent flow in an ESP, the laminar boundary layer would be expected to be similar to Fig. 3a. The maximum laminar velocity is close to the interface between the boundary layer and the turbulent zone. As the collector plate is approached, the laminar velocity decreases. At the collector/boundary-layer interface, the velocity is zero. Until a charged particle is collected, its migration velocity is always perpendicular to the laminar flow field and its trajectory is the vector sum of the two perpendicular velocities. For electrified fabric filtration, the flow in the boundary layers is surmised to be similar to Fig. 3b. For this case, the velocity in the axial direction also goes to zero at the laminar-boundary-layer/fabric-collector interface. However, it is replaced with a radial velocity, perpendicular to the fabric surface. The particle is no longer moving perpendicular to a laminar flow field, but is moving parallel with it. The resultant particle motion is now the vector sum of the two parallel velocities. This difference in the boundary-layer flow field will not be included in the model at this time. If it is found to be necessary, a correction factor might have to be included in the mathematical model to account for this additional radial velocity.

It is best also to develop the model for the electrified baghouse in incremental form because of the two collection mechanisms and to allow for the change in gas flow in the Deutsch–Anderson equation. If it becomes necessary to account for changing electrical conditions, from one point within a bag to another, the incremental model will allow it to be done.

The bag will be divided into l increments each of L/l length. For each increment, the quantity of dust collected, by both ESP and porous flow mechanisms, will be computed and summed for the collection in that increment. The ESP portion of the collection will be done incrementally for m narrow particle size bands; the collection due to flow through the porous filter is not size dependent. For increment j of the L/l length increments, collection by porous flow is the ratio of the gas flow through the porous filter media to the total amount of gas entering the increment. This is expressed mathematically as

$$G_j = \frac{(v_{j-1} - v_j)(\pi b^2/4)}{v_{j-1}\ (\pi b^2/4)} = \frac{v_{j-1} - v_j}{v_{j-1}} \tag{10}$$

It is asumed that the dust deposited by porous flow is equal to the fraction of the gas lost in that increment.The index $j-1$ indicates the inlet of increment j, and index j indicates the outlet of the increment. The velocity, v, for fabric filtration with integral particle charging and collection in a combined electric and flow field is computed using eqn. (6).

The ESP collection makes use of the Deutsch–Anderson collection equation, eqn. (8):

$$H_j = \sum_{i=1}^{m} [1 - \exp(-\overline{\mathrm{SCA}}_j w_{ji})] \tag{11}$$

In eqn. (11) the quantity A/Q, which is the gas flow per unit of collector area or SCA, is replaced with the average $\overline{\mathrm{SCA}}$ (Specific Collector Area). The index i is the particle size increment corresponding to migration velocity, w_{ji}.

In the application of eqns. (10) and (11), the particles entering the increment must be segregated into two groups that are subject only to porous flow and ESP collection, respectively. If this is not done, each collection quantity — porous flow and ESP — will act on all particles entering the increment and the model will seriously overpredict collection. This correction, as applied to the two collection quantities, leads to the relationship for the increment

$$N_{j-1} [1 - (1 - H_j) G_j - (1 - G_j) H_j] = N_j \tag{12}$$

The quantity N_{j-1} = amount of particulate matter or dust entering the increment and N_j = amount of particulate matter that exits from the increment.

The $\overline{\mathrm{SCA}}$, which is the average of the ratio of the collector area of the increment to the gas flow, is

$$\overline{\mathrm{SCA}} = \frac{\pi b L/l}{\frac{1}{2}(v_{j-1} + v_j)(\pi b^2/4)} = \frac{8L}{bl(v_{j-1} + v_j)} \tag{13}$$

The numerator is the area of the fabric filter collector surface in an increment. The denominator is the average gas flow in the increment. Note that, in an ESP, the SCA remains constant from one increment to the next; in fabric filtration with integral particle charging and collection in a combined electric and flow field, the $\overline{\mathrm{SCA}}$ increases in going up the bag.

The equation for the migration velocity, w, as a function of time, t, is

$$w = \frac{qE}{6\pi a\eta}\left[1 - \exp\left(-\frac{6\pi a\eta t}{m}\right)\right] \tag{14}$$

Equation (14) is a relationship for a particle of size a, charge q, and mass m, in an electric field E, and gas of viscosity η [11]. Because the particle accelerates to its terminal velocity in a very short time, compared to its residence time in an ESP or electrified bag, the exponential term may be dropped if desired. However, with modern computing equipment, it is just as easily left in.

The quantity q in eqn. (14) is the charge on the particle, which (at saturation for field charging) is

$$q_s = 12\pi a^2 \epsilon_0 E \tag{15}$$

in which the particle of diameter a has achieved its maximum charge in an

electric field E. The quantity ϵ_0 is the permittivity of free space, which is 8.85×10^{-12} F/m [11].

The charge on the particle at any time is obtained by multiplying the saturation charge by the term $1/(1+\tau/t)$ so that

$$q_t = q_s \frac{1}{1+\tau/t} \tag{16}$$

There is now a relationship for the charge, q_t, in respect to the saturation charge, q_s, as a function of time. The quantity τ is a time constant that determines the rate of charging. The shorter τ is, the shorter is the time of charging and vice versa [3].

The quantity τ for field charging is

$$\tau = \frac{4\epsilon_0}{N_0 e\mu} \tag{17}$$

in which the following new quantities are introduced: N_0, the concentration of unipolar ions; e, the electronic charge; and μ, the ion mobility [11].

If it is assumed that the current carried by the dust is negligible, which is usually the case in ESP work [11], then

$$N_0 e\mu = J/E \tag{18}$$

in which J is the current density corresponding to the field, E, near the collector surface.

Substituting eqn. (18) into eqn. (17) results in

$$\tau = 4\epsilon_0 E/J \tag{19}$$

Substituting eqn. (19) into eqn. (16) leads to

$$q_t = q_s \frac{1}{1+4\epsilon_0 E/Jt} \tag{20}$$

To be more correct, eqn. (21) could have the quantity $k/(k+2)$ inserted as a multiplier to account for the dielectric constant of nonconductive particulate matter. For the purpose of the model at this time, the effects of inserting the quantity $k/(k+2)$ will be assumed to have a negligible effect.

Finally, only field charging of particles has been considered for the model. For very fine particles, diffusion charging becomes important. Field charging is the dominant mechanism for particles with a diameter larger than 0.5 μm, and diffusion charging is dominant for particles less than about 0.2 μm in diameter. In the intermediate range, both charging mechanisms are usually considered [11]. For the present, only field charging will be considered.

Substituting eqns. (15) and (20) into eqn. (14) results in

$$w=\frac{2a\epsilon_0 E_1 E_2}{\eta(1+4\epsilon_0 E_3/Jt)}\left[1-\exp\left(-\frac{6\pi a\eta t}{m}\right)\right] \tag{21}$$

The migration velocity, w, is now related to the time that a particle of size a is subjected to field charging and is allowed to achieve its terminal migration velocity due to the action of an electric field. The charging field is E_1, the collecting field is E_2, and field E_3 had been related to the ionic space charge close to the collecting area, as was current density, J. The mass of the particle, m, is given by

$$m=\tfrac{4}{3}\pi a^3\rho \tag{22}$$

in which $a=$ diameter, and $\rho=$density.

Finally, to make eqn. (21) more useful, the migration velocity, w, is put in terms of position z in the bag, rather than in terms of time. This is done by noting in eqn. (6) that $v=\mathrm{d}z/\mathrm{d}t$, so that

$$\frac{\mathrm{d}z}{\mathrm{d}t}=\frac{4\bar{v}_f}{bL}(L^2-z^2) \tag{23}$$

Integrating eqn. (23), with the condition that $z=0$ when $t=0$, results in

$$t=\frac{b}{8\bar{v}_f}\ln\left(\frac{L+z}{L-z}\right) \tag{24}$$

which, upon substituting into eqn. (21) along with eqn. (22), gives

$$w=\frac{2ab\epsilon_0 E_1 E_2 J\ln\left(\frac{L+z}{L-z}\right)}{\eta\left[bJ\ln\left(\frac{L+z}{L-z}\right)+32\epsilon_0 E_3\bar{v}_f\right]}\left\{1-\exp\left[\frac{-9\eta b\ln\left(\frac{L+z}{L-z}\right)}{16a^2\rho\bar{v}_f}\right]\right\} \tag{25}$$

Equation (25) written for length increment j, and particle size increment i, is

$$w_{ji}=\frac{2a_i b\epsilon_0 E_1 E_2 J\ln\left(\frac{L+z_j}{L-z_j}\right)}{\eta\left[bJ\ln\left(\frac{L+z_j}{L-z_j}\right)+32\epsilon_0 E_3\bar{v}_f\right]}\left\{1-\exp\left[\frac{-9\eta b\ln\left(\frac{L+z_j}{L-z_j}\right)}{16a_i^2\rho\bar{v}_f}\right]\right\} \tag{26}$$

In eqn. (26), $a_i=$mean diameter of particle increment i, and $z_j=$location of the mean value of z of increment j.

By using eqn. (12), the nonuniform dust layer deposition of fabric filtration with integral particle charging and collection in a combined electric and flow field can be computed as a function of bag geometry and electric and flow

conditions. The computed nonuniform deposition will be used to calculate the relative pressure drop.

The nonuniform deposition model predicts the quantity of dust deposited in each increment. For nonelectrified or conventional filtration, the dust layer will be uniform. It is assumed that the total dust and the average gas-to-cloth ratio, v_f, for both uniform and nonuniform deposition are the same and that the amount deposited in any increment is the areal density. From the relationship for parallel resistances, remembering that the drag, S, is a resistance, it follows that

$$\bar{S}_n = \left(\sum_{j=1}^{l} \frac{1/l}{S_j} \right)^{-1} = l \left(\sum_{j=1}^{l} \frac{1}{k_2 W_j} \right)^{-1} = l k_2 \left(\sum_{j=1}^{l} \frac{1}{W_j} \right)^{-1} \tag{27}$$

in which $\bar{S}$ = average drag, l = number of increments, W_j = areal density of the dust deposited in increment j from eqn. (2), and $1/l$ = fraction of the total bag area for each increment. It is necessary to make the calculation in terms of area because the drag is a resistance per unit area. The average drag, $\bar{S}$, is also in terms of a fractional area, which for the whole bag is equal to 1.

The drag for the uniform dust layer, assuming that the total mass of dust deposited is the same as for the nonuniform case, is

$$\bar{S}_u = k_2 W \tag{28}$$

The uniform and nonuniform cases are doted by the subscripts u and n, respectively.

By using eqn. (3) and assuming constant k_2, the ratio of the ΔP for the nonuniform and uniform cases is

$$\frac{\Delta P_n}{\Delta P_u} = \frac{\bar{S}_n}{\bar{S}_u} \tag{29}$$

The ratio $\bar{S}_n/\bar{S}_u$ in eqn. (30) is

$$\frac{\bar{S}_n}{\bar{S}_u} = \frac{l \left(\sum_{j=1}^{l} 1/W_j \right)^{-1}}{W_u} \tag{30}$$

4. Verification of the model

The model was put into a programmable calculator to compute the nonuniform deposition. The particle size increments that were chosen are shown in Fig. 4 for the log-normal distribution, based on the measured geometric mass mean diameter of 3.3 μm and geometric standard deviation of 2.9, for the redispersed Southwestern Public Service (SWPS) fly ash. Figure 5, which is a cumulative

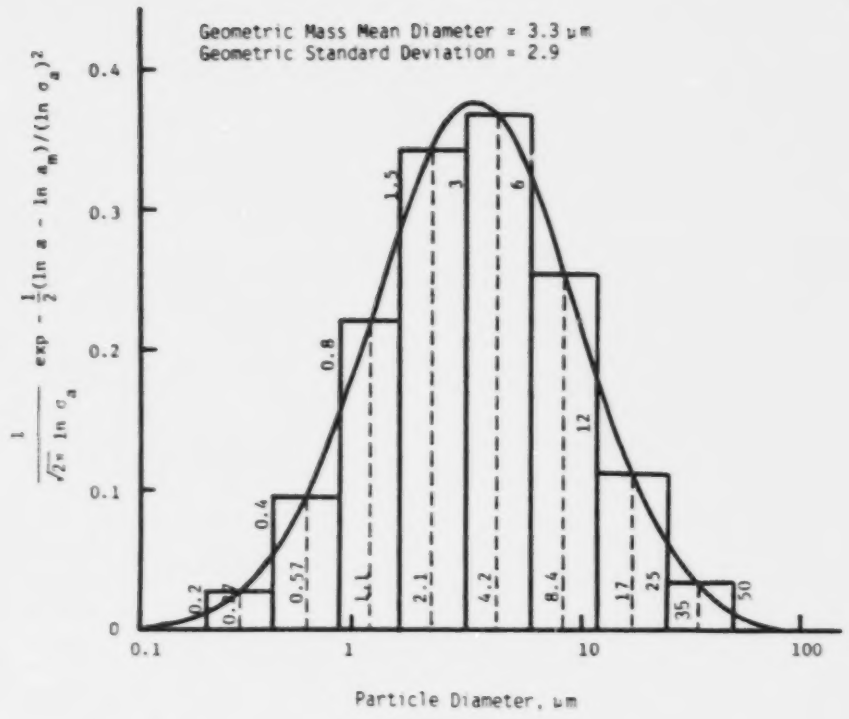

Fig. 4. Log-normal distribution of redispersed SWPS fly ash with particle size increments.

percent plot of the same SWPS fly ash by size, provides the percentage weight of each increment. For each model run, the bag was divided into 10 increments. When the model is eventually programmed for a high-speed computer, more increments could be used for improved accuracy.

The model calculations were performed for several of the test runs which are presented as histograms in Figs. 6 to 9. Test measurements had been reported previously [1,2].

Figure 6 is for a relatively low electric field and fairly high current density — approximately 500 kV/m and 4.5×10^{-4} A/m^2, respectively. The fabric in this test contained woven-in stainless steel yarns. The high current density causes initially rapid charging of the dust and collection of a large amount of the material close to the inlet. This model run shows a rather interesting result in that the amount of dust deposited in increment 10 is slightly larger than for increment 9. In an ESP a fraction of the particulate matter is uncollected and is discharged along with the exiting gas. The same phenomenon would be ex-

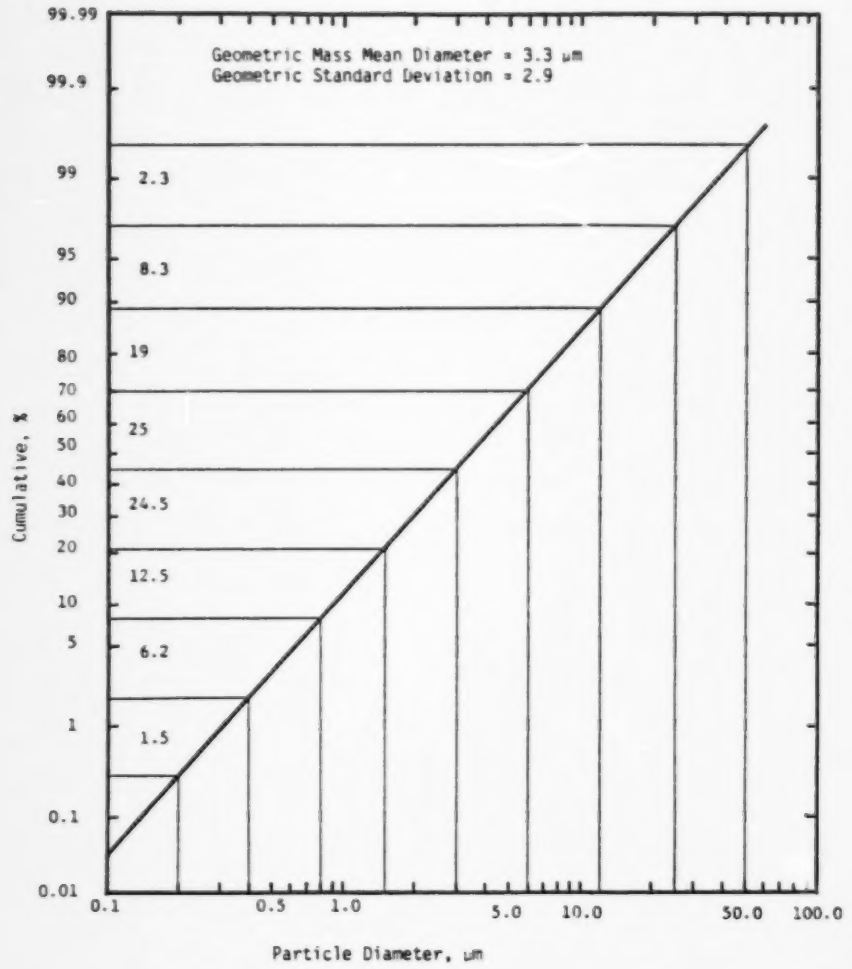

Fig. 5. Cumulative plot for redispersed SWPS fly ash showing percentage for each increment.

pected in the electrified bag if the electrical conditions are not sufficient to cause a high ESP effect. In this test the electrical field was not as high as in some of the other tests. In the filtration bag, these particles would be expected to be collected at the end of the bag as the final gas passes through the fabric. This was actually seen to happen in this test [2] as well as in several other tests.

Figure 7 is presented as two different computations. The model computation

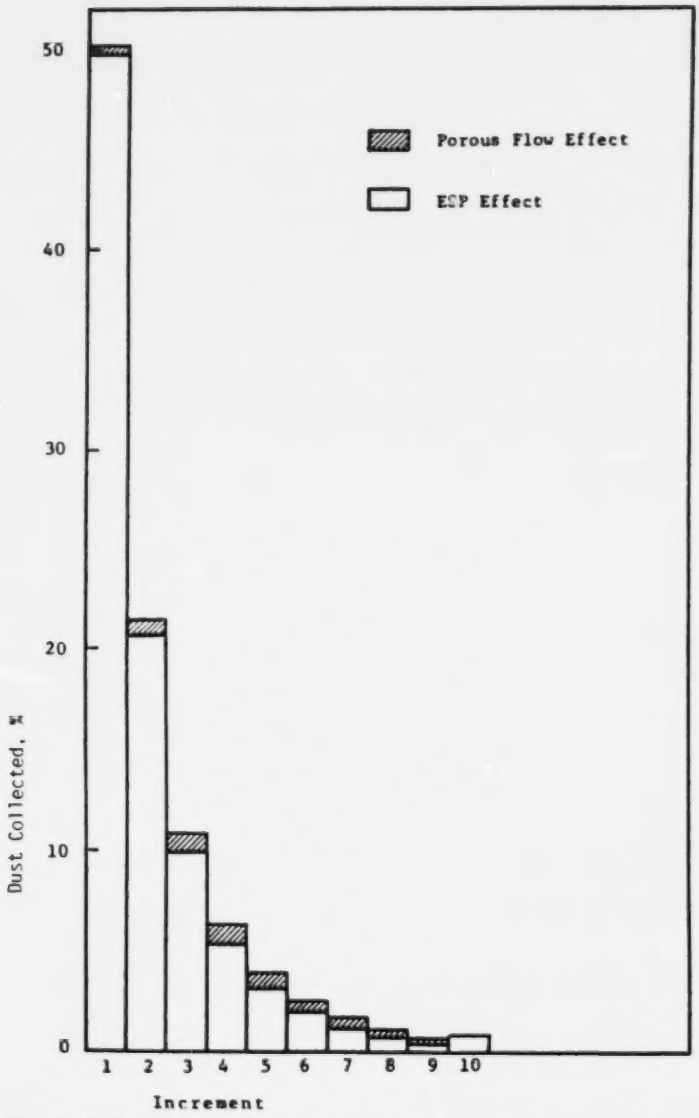

Fig. 6. Mathematical model prediction of nonuniform distribution for an electric field of 500 kV/m and current density of 4.5×10^{-4} A/m^2.

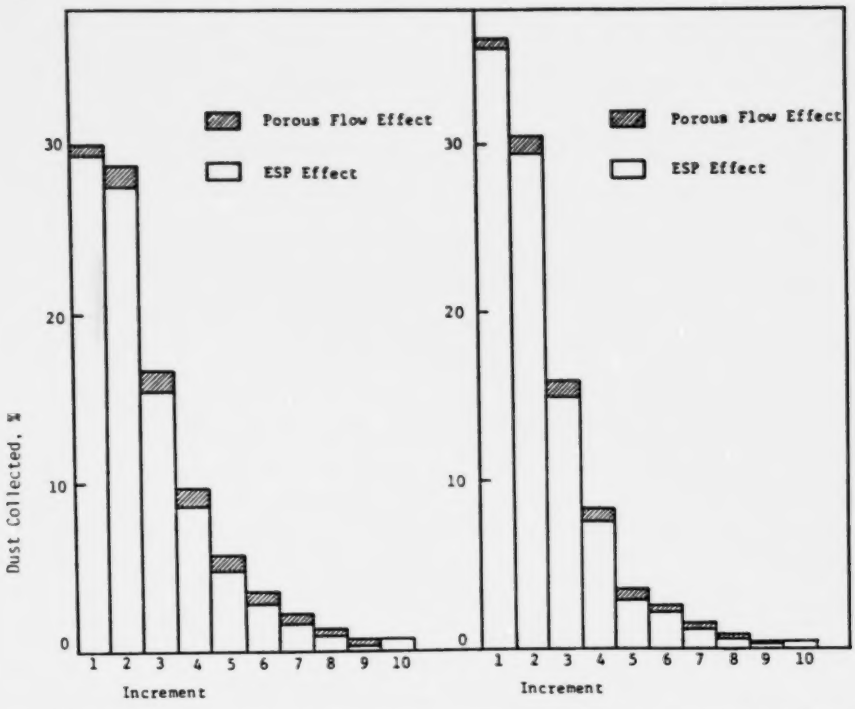

Fig. 7. Mathematical model prediction of nonuniform distribution for an electric field of 780 kV/m and current density of 6×10^{-5} A/m^2 as shown on the right side. The electric field for the left-hand portion has been decreased to 630 kV/m.

on the right is for the full 50 kV (780 kV/m) that was applied to the bag. The computation on the left side of Fig. 7 assumed that only 40 kV (630 kV/m) was applied. It had been noted during the experimental work [2] that the bags not containing the woven-in stainless steel yarn had a high surface charge on the dust layer. A computation was made with the reduced electric field to determine the effect of the surface charge. The higher voltage causes more dust to be collected initially because of both the higher level of charge and stronger field. There is also a thinner layer of dust in the upper portion of the bag with the higher field. For both tests the average current density was 6×10^{-5} A/m^2.

Figure 8 is for a test in which the field was set at 750 kV/m and the current density was 3×10^{-5} A/m^2. The model predicted that there would be a lower areal density in increment 1. The model assumes neutral charge on all particles entering the bag. It is well known from the field charging equations that, for low current densities, it takes longer for particles to acquire saturation charge than for higher current densities. The current density for this test was lower

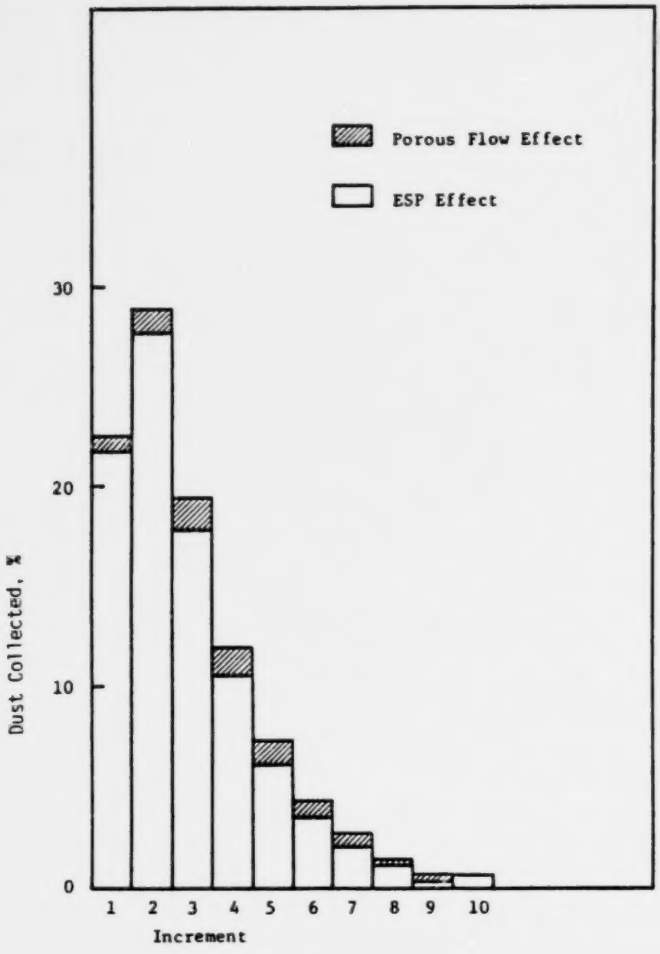

Fig. 8. Mathematical model prediction of nonuniform distribution for an electric field of 750 kV/m and a current density of 3×10^{-5} A/m^2.

than that for the tests shown in Figs. 6 and 7. In examining the actual test results for the test of Fig. 8, the effect of lower areal density at the bottom of the bag was not seen. This is probably due to charge separation. Even though the particles, in total, were essentially neutral, they still contain a number of both positive and negative particles when entering the bag; the negative charged particles would tend to deposit because of the electric field. Several of the test runs, which operated with fairly low current densities, gave indications of decreased collection at the bottom of the bag [2].

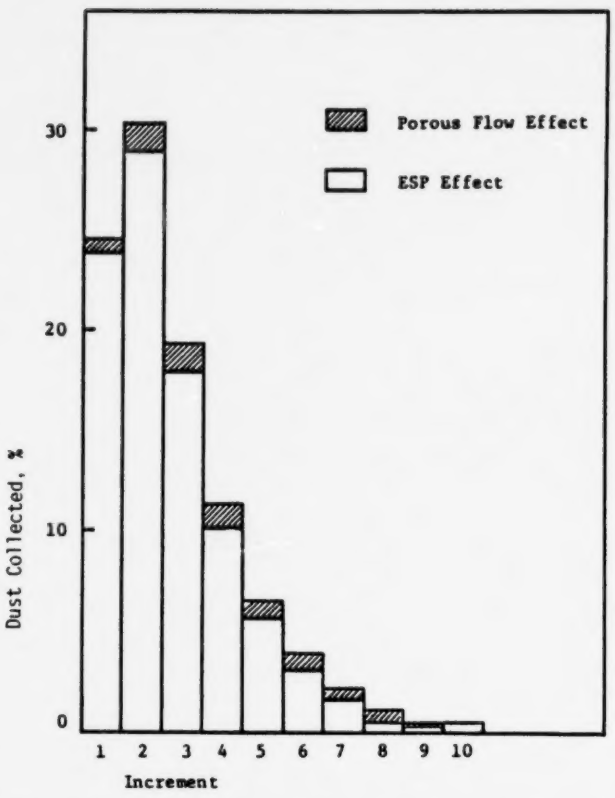

Fig. 9. Mathematical model prediction of nonuniform distribution for an electric field of 630 kV/m and a current density of 1×10^{-5} A/m^2.

Figure 9 is for a test in which the current density was 1×10^{-5}A/m^2 and the electric field was 630 kV/m. The original tests did show evidence of lower areal density at the bottom of the bag, which is consistent with the model prediction. Also of interest is that, for this test run, the gas/cloth ratio was set at 0.01 m/s, which was half of the gas/cloth ratio for most of the other runs. What this does is double the average SCA for each increment. It would be expected from eqn. (11) that, if SCA were increased in each increment, the collection due to the ESP effect would increase. For this reason, the model predicts a higher collection than would be expected for the electrical conditions.

The model was used to predict the expected nonuniform dust deposition at the EPA-owned pilot baghouse at SWPS [1] using the electrical conditions that have been reported [12]. It is assumed that the particle size distribution at SWPS was similar to that for the redispersed dust in the laboratory tests.

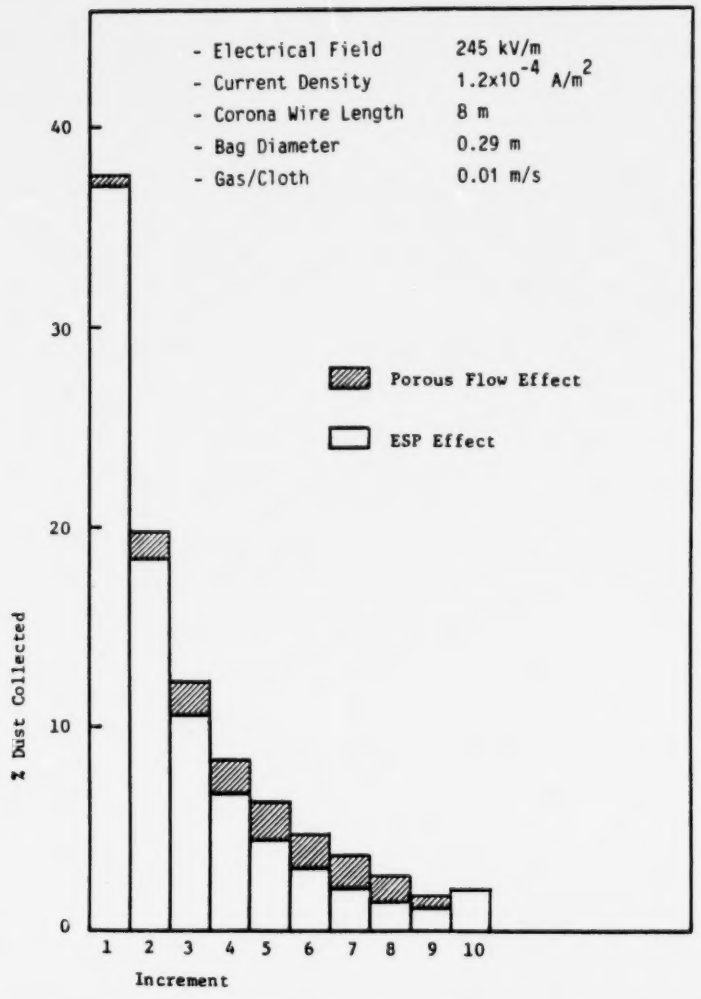

Fig. 10. Mathematical model prediction of nonuniform distribution using the SWPS pilot unit electrical conditions.

This assumption is believed to be reasonable. The results are shown in Fig. 10. The low field strength, 245 kV/m, also caused the model to predict a higher areal density in increment 10 than in increment 9. The electrical conditions were the average for five bags. At SWPS the current distribution among the bags was poor.

Finally, the model was applied to the second fabric filtration field pilot unit

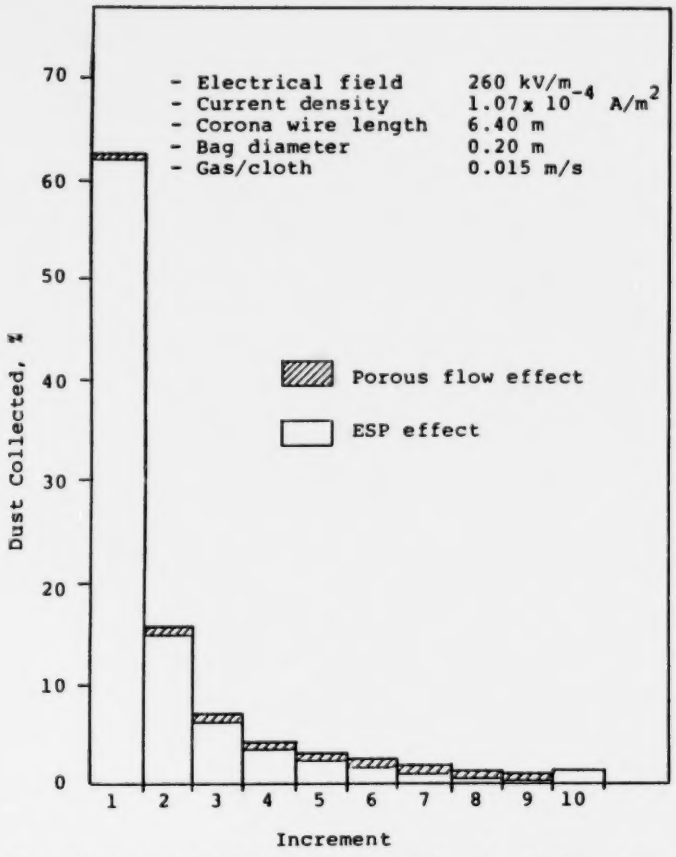

Fig. 11 Mathematical prediction of nonuniform deposition for the spreader-stoker pilot unit electrical conditions.

in which integral particle charging and collection in a combined electric and flow field had been used [1,13,14]. The spreader-stoker boiler's ash contained a large amount of unburned carbon, which caused it to have a resistivity of 1×10^5 Ωm or less. The particle size distribution of a spreader-stoker boiler differs from that of the pulverized-coal boiler used at SWPS. The precise size distribution of the fly ash was not known; therefore, a typical value had to be used. A reported value for a spreader-stoker boiler showed a geometric mass mean diameter of 18.4 μm and a geometric standard deviation of 5.2 [15]. The size distribution was plotted in the same manner as the SWPS fly ash in Figs. 4 and 5. The higher geometric mass mean diameter and geometric standard deviation indicate that there would be more large particles and fewer fines in the spreader-stoker ash than in the SWPS ash. This suggests that the spreader-

TABLE 1

Relative pressure drop computations

No.	Figure No.	Test type	Relative ΔP
1	6	Laboratory	0.20
2	7	Laboratory	0.13
3	7	Laboratory	0.22
4	8	Laboratory	0.24
5	9	Laboratory	0.17
6	10	Large pilot unit	0.43
7	11	Large pilot unit	0.22

stoker ash would have a greater ESP collection effect than the SWPS ash.

The mathematical model nonuniform dust layer prediction, based on the spreader-stoker field pilot unit electrical conditions, is presented in Fig. 11. It is apparent that the ESP collection effect for the spreader-stoker combustion baghouse electrical conditions was considerably greater than those for the SWPS field pilot unit.

The mathematical model was used to calculate the relative pressure drop for the nonuniform dust layer distributions shown in Figs. 6 through 11. The relative pressure drop computations are presented in Table 1.

5. Discussion of the results from the model prediction

In general, the predicted relative pressure drops based on the laboratory test electrical conditions did not agree closely with the actual laboratory results. As an example, the actual test results for the model prediction of Fig. 6 had the lowest measured average pressure drop. This was probably caused by back corona and dust blown off the fabric by the relatively high current densities. It is believed that local poor electrical conditions have a much more significant effect on small bags than on the larger ones that are used commercially. In addition, the small bags used for the laboratory tests did not have turbulent flow. In the development of the mathematical model, the flow is assumed to be turbulent.

Some indication of the model prediction, which assumes turbulent flow, compared to laminar flow collection is presented in Fig 12. The turbulent flow deposition computation had used the model. The laminar flow deposition pattern used a migration velocity calculation that was multiplied by the time to determine the percentage of 1 μm dust that would be collected in each increment. For laminar flow, the model overpredicts collection in the inlet section of the fabric filter bag and underpredicts in the upper portion. To some extent

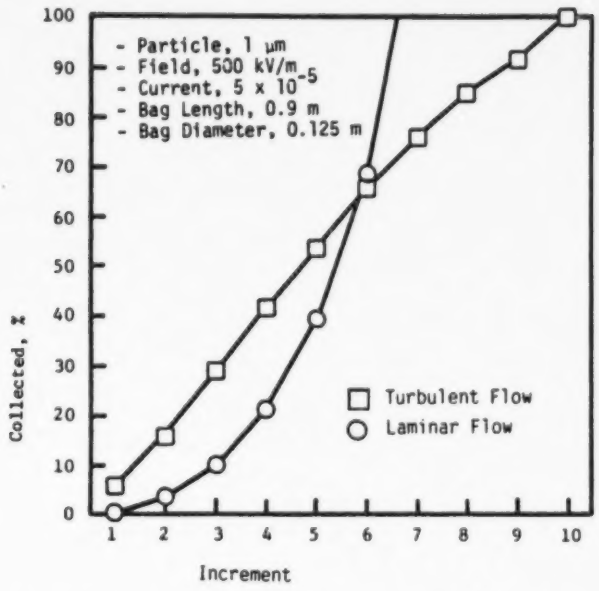

Fig. 12. Calculation of collection by increment in a laminar flow field using calculation based on laminar and turbulent flows.

the over- and under-predictions are self-compensating. However, the extent to which they are self-compensating is not known. There will not be many practical applications for small electrified bags operating in the laminar flow regime; therefore, modifying the model for computation of collection in small laminar flow bag filters is of little concern.

Of greater importance are larger bags operating in the turbulent flow regime. The two large field pilot plants — EPA's SWPS and spreader-stoker units — are typical of the sizes used in industry.

At the start of the filtration in the EPA/SWPS field pilot unit, with the bags clean, the relative pressure drop was 0.44 [12]. The model using the electrical conditions for the pilot unit predicted a relative pressure drop of 0.43, which is quite close to the measured value.

The predicted relative pressure drop for the EPA spreader-stoker pilot plant from Table 1 is 0.22. Unfortunately, the pressure drop for the conventional and electrified bags could not be reported directly. Both the conventional and electrified bags were in the same baghouse compartment and were thus exposed to the same pressure difference. Instead the gas flow through each bag was measured with special individual flow monitors [14]. By use of the relationships developed for fabric filtration [1], an expected pressure drop rise (PDR) during the filtration cycle was computed. The ratio of the PDR, of the electrified

to conventional filtration, was in the range of 0.2 to 0.3. If the conventional and electrified bags were in separate compartments, the pressure drop in the compartment having integral particle charging and collection (in a combined electric and flow field) would be 20 to 30% of that for conventional filtration. The prediction is considered to be reasonable.

The limited data suggest that, in fabric filtration baghouses containing large bags, the model predicts better than it does in small laboratory bags. This is believed to be due to the former's having turbulent flow and better electrical operation.

6. Conclusion

The application of electrostatics to fabric filtration in the form of integral particle charging and collection in a combined electric and flow field causes it to dominate the collection, compared to porous flow collection. It causes nonuniform deposition of particulate matter or dust with the maximum at the open end and the minimum at the closed end.

The nonuniform deposition causes a lower pressure drop than the uniform deposition of conventional filtration. The lower pressure drop can be used to decrease either fan power (thereby causing annual savings) or the number of bags required for filtration (thereby providing capital savings).

As a consequence of the above findings, it would be expected that a fabric filtration baghouse having integral particle charging and collection in a combined electric and flow field should, at least, be expected to operate at about 30% or better of the pressure drop of a nonelectrified baghouse with reasonable electrical conditions.

Currently, inside-to-outside-flow baghouses typically operate at a gas-to-cloth ratio of about 0.01 m/s. If a more vigorous cleaning technique such as shake/deflate is used, baghouses will operate at a gas-to-cloth ratio of 0.015 m/s. Fabric filtration with integral particle charging and collection in a combined electric and flow field, because of its lower pressure drop, has the potential to operate stably at gas-to-cloth ratios considerably greater than 0.01 m/s.

A mathematical engineering design model has been developed to predict the nonuniform dust deposition and relative pressure drops. Based on a relatively small amount of data, the model predicts at least qualitatively, if not somewhat quantitatively, the relative pressure drop that should be achieved as a function of varying the electrical conditions applied to the electrified fabric filtration baghouse. The mathematical model uses well-known electrostatic and gas flow relationships. The assumptions that have been used are reasonable.

The mathematical model for fabric filtration with integral particel charging and collection in a combined electric and flow field is usable as an engineering design tool for application and development of the technology.

As additional data are generated, they should be used to increase the accu-

racy of the mathematical engineering design model in the form of corrections such as were applied to the ESP model in its evolutionary development.

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